Towards a Complete Methodology for Mine Water Impact Assessment and Site Remediation.

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Abstract

Mine water pollution is now a significant cause of pollution in the UK. As a result methods of impact assessment and remediation for mine waters have received significant attention in recent years. Two different methods of impact assessment are outlined[1][2]. Iron load and acidity load are not included in either of these methodologies, but perhaps should be due to the significance of these variables with regard to water resources and supply. Further, iron load and/or acidity load are critical for the design of constructed wetlands for mine water remediation. Once completed, impact assessment data can be used as a first step in the design of remediation schemes. The construction of a small wetland for mine water treatment at Quaking Houses, County Durham, serves as a basis for outlining the best approach to implementing remediation schemes. After initial 'scoping' of treatment options a thorough site evaluation is recommended, which should include investigations of land area available, site gradient and topography, together with issues of vehicular access and materials availability. Selection of the most appropriate treatment option can then be accomplished. The resultant design can be revised according to a total costing if necessary. Approaching mine water impact assessment and remediation in this manner is considered to be the most resource efficient and effective, which is critically important given a scenario of limited financial backing for such schemes.

Keywords: mine water pollution; impact assessment; site evaluation; wetlands; remediation; iron load; acidity load.

Introduction

Aquatic pollution caused by discharges from abandoned mines and spoil heaps is now a well documented phenomenon[3][4]. The most recent best estimate of the length of watercourse in England and Wales affected, 200 km[5], is now felt by many researchers to be a conservative estimate.

The root cause of mine water pollution (often termed Acid Mine Drainage (AMD)) is localised lowering of water-tables through pumping activities, undertaken in order to access deep coal seams. Subsequent cessation of pumping, following mine closure,

TABLE 1. Chemical data for an abandoned coal mine discharge (A) and a spoil heap leachate (B)[7].

PARAMETER	Tindale Colliery (A) (G.R. NZ 197269)	Crook (B) (G.R. NZ 185356)
Flow-rate on 15.4.94 (m^3/s)	0.01	0.002
Calcium (mg/L)	262	185
Magnesium (mg/L)	107	93
Sodium (mg/L)	80	21.5
Potassium (mg/L)	13	6.8
Iron (mg/L)	1.8	79.8
Manganese (mg/L)	1.7	6.9
Aluminium (mg/L)	0.04	4.2
Zinc (mg/L)	0.02	0.05
Copper (mg/L)	0.01	0.23
Alkalinity (mg/L as $CaCO_3$)	357	0.00
Sulphate (mg/L)	890	810
Chloride (mg/L)	75	65
pH	6.4	4.8
Temperature (°C)	12.0	11.8
Eh (mV)	- 50	264
Conductivity (μS/cm)	2360	1563

TABLE 2. Impacts of mine water pollution and associated groundwater rebound[8].

IMPACT	CAUSE	CONSEQUENCES
Water Resources	Discharges of mine water into surface watercourses	1. Threat to water supply due to increased iron (and other metal) load. 2. Biological communities severely impoverished, ultimately leading to loss of fish and associated wildlife. 3. Loss of amenity value.
Agriculture	Uncontrolled emergence of mine water at surface	1. Loss of land due to inundation of recently emerged mine waters. 2. Potential hazard to livestock.
Built environment	Rising groundwater levels.	1. High sulphate concentrations of rising groundwaters can lead to corrosion of cement and possible collapse of buildings. 2. Leaching of pollutants from landfills formerly above water-table. 3. Possible increase in flow in old sewers in low lying areas leading to problems at water treatment works.

allows water levels to rise. However oxidation of the mineral pyrite (FeS_2), common within the coal measures, results in rising waters being highly charged with ferrous iron. On discharge to the surface environment the ferrous (Fe^{2+}) iron in these groundwaters is rapidly oxidised to the ferric (Fe^{3+}) state, resulting in rapid deposition of iron oxyhydroxide on stream beds. As a consequence receiving watercourses may be thickly coated in deposits of red or orange "ochre", causing unsightly discolouration, and impoverished aquatic ecology(4)(6). Other metals may also be present at elevated concentrations, particularly manganese and aluminium. Drainage from spoil heaps, wherein the processes of pyrite oxidation and hydrolysis appear to be particularly vigorous, is invariably acidic (Table 1) and can be highly charged with aluminium, manganese, copper and zinc. Table 1 illustrates chemical values for an abandoned coal mine and a spoil tip discharge in the Durham coalfield of north east England.

Given the extent and severity of this pollution problem, the impacts of which are detailed in Table 2, it is most unfortunate that the Water Resources Act 1991 (England and Wales) provides little power for the national regulator (the Environment Agency) to take action regarding discharges from abandoned mines. Section 85(1) of the Water Resources Act 1991 stipulates that a pollution offence is only committed if a mine owner:

"....*causes or knowingly permits* any poisonous, noxious or polluting matter or any solid waste matter to enter any controlled waters".

Proving this causality is so difficult that there has only been one successful prosecution of a mine owner in the UK to date(5).

As a result there is little financial support for initiatives to treat discharges from abandoned mineworkings and spoil tips in the UK and, as a consequence, it is therefore vital that regulators and researchers have a very clear picture of how to approach assessment and remediation of mine water pollution. Otherwise valuable time and resources may be wasted, irrespective of the 'pure' research interest of a particular line of enquiry. The following paragraphs address the critical issues in successful site evaluation for remediation initiatives and mine water impact assessment.

Importance of Impact Assessment and Site Evaluation

Chronologically, it is normal for an impact assessment to precede any form of site evaluation. The former enables a quantitative (or semi-quantitative) assessment of the severity of the discharge, and usually forms the decision-making basis for selection of mine waters requiring remediation. Such is the extent of mine water pollution in the UK that to anticipate treatment of all discharges is unrealistic.

Impact assessments are essential for prioritising action, and have particular application to:

(i) Targeting discharges for remediation.

TABLE 3. NRA ranking strategy[4], and AMDI results[2] for 5 North-east mine waters.

(A) Physicochemical ranking

RANK	Minewater	Area affected (m^2)	Length affected (m^2)	Substrate quality	Iron deposition	Iron concentration	pH, DO, [Al]	**AMDI**
1	Acomb	1500 (B1)	1.00 (A)	A	A	32.5 (A)	7.2, 69, 0.06 (C)	**69**
2	Edmondsley	1950 (B1)	0.65 (A)	A	A	8.4 (A)	7.2, 77, 0.03 (D)	**68**
3	Lowlands	2250 (B1)	0.60 (A)	A	A	2.0 (B)	7.1, 78, 0.06 (D)	**79**
4	Lambley	1925 (B1)	0.35 (B)	A	A	3.3 (A)	6.6, 44, 0.05 (B)	**85**
5	Helmington Row	525 (B2)	0.60 (A)	A	A	53.4 (A)	3.2, 51, 47.4 (A)	**36**

(B) Biological (final) ranking

RANK	Minewater	Biological impact (% decrease BMWP, Δ Log_{10} abundance)	Area affected (m^2)	Fisheries potential	**AMDI**
1 (2)	Edmondsley	57.7%, 6 (A)	15000 (A)	B1	**68**
2 (4)	Lambley	61.2%, 9 (A)	325 (B)	A	**85**
3 (1)	Acomb	97.1%, 7 (A)	1500 (B)	B1	**69**
4 (5)	Helmington Row	87.3%, 4 (A)	1300 (B)	C	**36**
5 (3)	Lowlands	37.3%, 8 (B)	6750 (A)	B1	**79**

(ii) Long-term monitoring of polluting discharges.
(iii) Selecting the most appropriate remediation technologies, if correctly devised.

In terms of remediation, *passive* treatment (no-ongoing inputs of energy or chemicals) has received close attention in recent years due largely to the low revenue costs involved. However, passive treatment systems demand large areas of land and, since these systems rely on gravity flow, the selected site must have an acceptable topography. Thus, in most cases, site evaluation is essential prior to any decision on which treatment technology is appropriate. At the most basic level two vital questions must be asked:

1. Is there sufficient land area to build the required system?
2. Will there be sufficient head to drive the mine water by gravity through the treatment system?

A case study of a constructed wetland scheme at Quaking Houses, County Durham, serves as a basis for more detailed discussion of this latter topic in the following paragraphs.

Current Methods Of Impact Assessment

The most widely used impact assessment methodology in England and Wales is that of the national regulator, the Environment Agency (formerly the National Rivers Authority (NRA)). Originally developed by the Welsh Region of the NRA(1)(3), the system has now been applied to affected watercourses in the north east(4) and north west of England in a national ranking exercise.

The system accounts for physicochemical and biological characteristics of receiving watercourses, in two stages:

Stage I: Ranking according to physicochemical impact of the mine water on the receiving watercourse.
Stage II: Final ranking, based on biological impact.

In Stage I ranking the most critical variable is the area affected by ochre deposition. According to the area of receiving watercourse deemed to be affected by ochre deposition (a visual assessment) the mine water of interest is categorised as HIGH (A), MEDIUM (B), LOW (C) or NO (D) impact. The relative impact of each subsequent assessment variable (length affected, substrate quality for salmonid reproduction, iron deposition (visual), total iron (mg/L), and pH/dissolved oxygen/aluminium) is then assessed, resulting in a ranked list such as that illustrated in Table 3(A).

Stage II is a biological assessment based on benthic invertebrate welfare. Stage II is usually only applied to the top percentage of those mine waters ranked in Stage I, and the resultant list is considered as the final ranking. Two criteria are used:

(i) Biological impact and
(ii) Area biologically impacted.

Both are calculated from the Biological Monitoring Working Party (BMWP) biotic index. Biological impact is assessed by calculating the percentage decrease in BMWP score between an upstream site and a site immediately downstream of the mine water discharge. Area affected is calculated by finding the point downstream in the receiving watercourse at which the BMWP score returns to its upstream value (Table 3(B)).

A Water Quality Index (WQI) specifically for use at Acid Mine Drainage (AMD) sites has also been developed(2). The Acid Mine Drainage Index (AMDI) is based on chemical parameters only. Individual scores are given to seven critical parameters (pH, sulphate, iron, zinc, aluminium, copper and cadmium concentrations) according to their concentrations and a specified weighting factor. AMDI is then calculated by:

$$\text{AMDI} = [\Sigma \text{ water quality scores}]^2 / 100$$

A water-quality rating table was produced to simplify calculation of the AMDI. Thus, individual water quality scores are simply summed, squared, and divided by 100 to calculate AMDI(2). A low score is indicative of a severely polluting discharge.

Significant differences between AMDI values for discharges, mixing zones and recovery zones of receiving watercourses could be discerned for the site under investigation(2).

AMDIs for 5 North-east mine waters are included in Table 3. Even a cursory glance reveals that there is little similarity between the NRA ranking and the AMDI. Correlation of results from 18 mine waters confirms that there is no statistical relationship between the two ranking methodologies. Given the variables on which each system is based, the immediate conclusion is that the chemical quality of a mine water (AMDI) is not necessarily indicative of the impact it will have on a receiving watercourse (NRA ranking).

The NRA ranking methodology provides a detailed picture of receiving watercourse impacts, although many of the categories (e.g. area and length affected, severity of iron deposition) are subjective assessments, and are therefore prone to inaccuracy. However, most significantly for researchers interested in both impact assessment and remediation, there is currently no system of assessment available which can be used directly as a tool for designing remediation systems. The critical variable missing from current impact assessment methodologies is the flow-rate of the mine water discharge. Simultaneous measurement of flow-rate, iron concentration and/or acidity concentration would allow calculation of the critical contaminant loads. The iron load (for net-alkaline discharges) or the acidity load (for net-acidic discharges) is the critical design parameter for passive mine water treatment schemes(9). If these two parameters were included in impact assessments all the physicochemical data required for design of remediation systems would be immediately available. Furthermore, an assessment of critical contaminant load input to a watercourse would provide an as yet unspecified indication of mine waters' threat to water supply systems, on a catchment-to-catchment basis.

The importance of iron load or acidity load for treatment design cannot be overemphasised. If flow-rate is not measured simultaneously to iron / acidity concentration load cannot be calculated, as one or both will certainly vary temporally. Thus, even a full year of chemical data are of little use without the flow-rate, in terms of design. Valuable time and resources could thus be saved if flow-rate was measured in the first instance, as part of an impact assessment.

Site Evaluation

Beyond the initial requirement for a complete set of data for a given mine water discharge (ideally over a full year, since most mine waters exhibit seasonal variability) other considerations must also be made regarding remediation. The following paragraphs describe some of the experiences gained by researchers at Newcastle University during the on-going design and construction of an engineered wetland for mine water treatment at Quaking Houses, County Durham. In particular, areas where time and resources could perhaps have been saved are highlighted. It is hoped that such a discussion may serve as a blueprint for future remediation schemes. It should be stressed, however, that remediation initiatives all appear to have a significant element of site-specificity, and therefore the following format (in particular Figure 1) will inevitably require adapting to the particular requirements of a project. Ultimately, therefore, the success of a treatment scheme rests with the experience and expertise of the workforce involved.

The Stanley Burn is a minor tributary of the River Wear, County Durham. At the head of the Stanley Burn an acidic, ferruginous, and aluminium-rich discharge enters the watercourse (Table 4), causing severe pollution of the Burn for over 1 km of its length. The discharge emanates from the spoil heap of the now abandoned Morrison Busty pit.

In 1995 a pilot-scale constructed wetland was built adjacent to the discharge. This small anaerobic wetland treated up to 10% of the flow from the discharge. Subsequent monitoring revealed that the wetland had an average acidity removal rate of 9.6 $g/m^2.d^{-1}$, and up to 80% of the iron content was removed[10]. Thus, the pilot-scale wetland performed admirably. In June 1996 work began on a constructed wetland at Quaking Houses to treat the entire discharge. At the time of writing construction is about to begin. The following paragraphs detail some of the most pertinent findings which have come from this experience to date.

Figure 1 illustrates the various elements of the wetland project at Quaking Houses. The flow chart shows, in chronological order, the most efficient approach to the development of a small constructed wetland for mine water treatment.

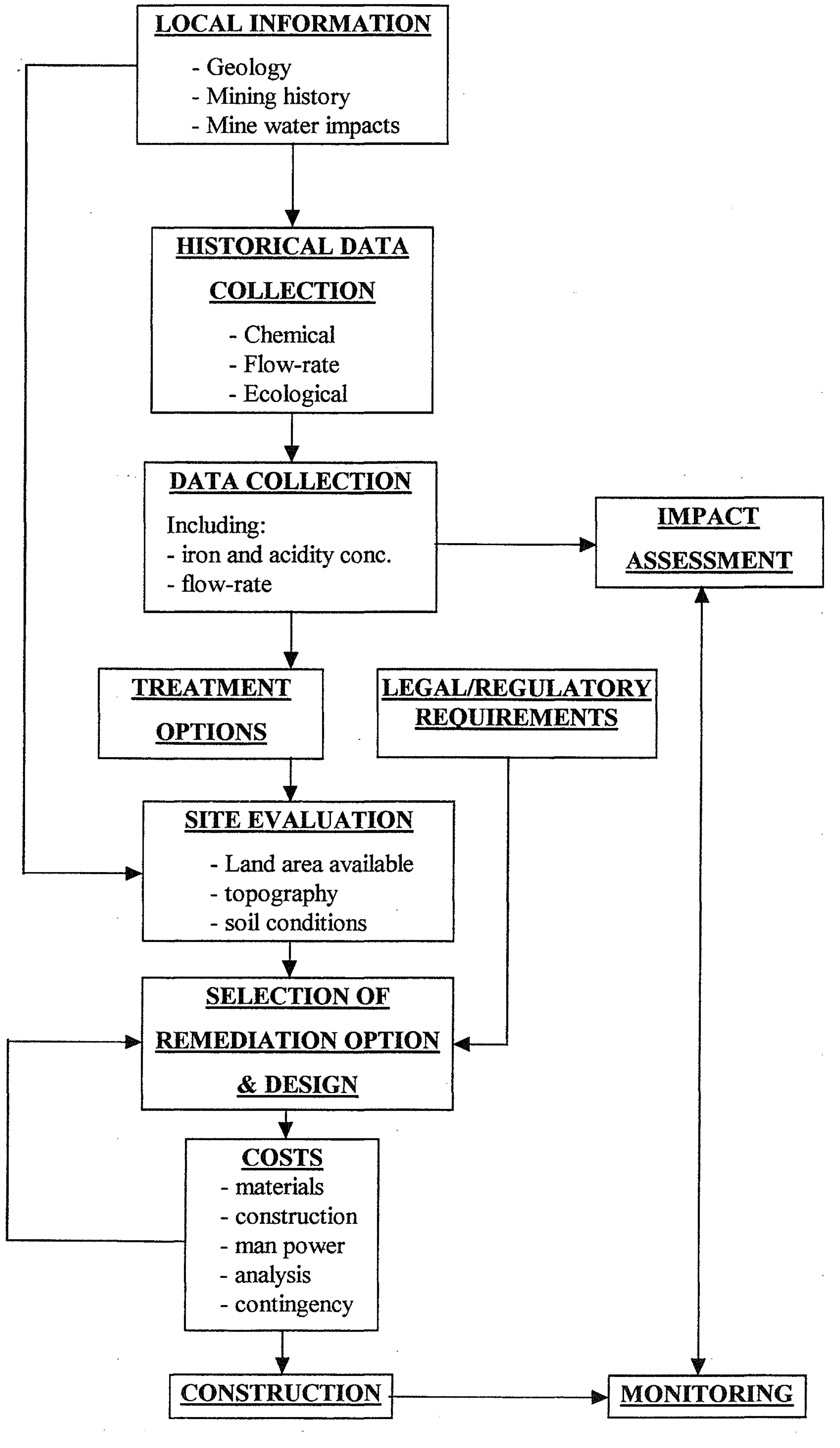

FIGURE 1. Site assessment and remediation methodology flow chart.

Any remediation scheme should begin with a detailed desk study investigating current available information about the planned site for locating any treatment units and the polluting discharge itself. Specifically this may entail collating chemical and ecological data pertinent to the discharge, often available from national regulators (the Environment Agency for England and Wales in this case). Land ownership and availability, usually accessible through local authorities, is also crucial. Other information can often be gained from local communities. This may include details of historical mining activity in the area and information regarding the age and nature of discharges. Further data collection can then focus on specific analytes of interest. This will almost certainly include iron concentration and acidity concentration, both critical design parameters for constructed wetlands. Experience has demonstrated that there is often a paucity of flow-rate data for mine water discharges, and collection of up to a years data should be a priority (with simultaneous measurement of iron and/or acidity concentration). It appears that the lack of flow-rate data may be due largely to the difficulty and cost of measuring this variable, but even where a simple 'bucket and stopwatch' measurement is not possible strenuous efforts to install some other form of flow measurement equipment, such as a V-notch weir or H-flume, should be made.

Thorough completion of the tasks outlined above should enable an accurate impact assessment to be made if the discharge characteristics are complemented with data for the receiving watercourse. Any impact assessment made can then be used as a point of reference for monitoring the effectiveness of any remediation schemes subsequently implemented.

In view of the data collected an initial assessment of realistic treatment options may then be possible. Chemical data will reveal whether anaerobic or aerobic constructed wetlands are more appropriate, and whether Anoxic Limestone Drains (ALDs) are required. Constructed wetland sizes can be calculated from critical contaminant loads[9]. Equally, potential size and cost of an active treatment scheme may be calculated. This initial assessment of treatment options will allow researchers to focus on the essential site characteristics which need to be quantified. However, there is little future in entering into the time consuming process of detailed design until the critical site characteristics are known. Thus site evaluation should proceed after this initial period of 'scoping' for treatment options.

There are many facets to site evaluation, and a thorough approach at this stage appears to be a key aspect of overall success. Table 5 summarises the essential factors for consideration. Questions regarding land area, gradient and topography can all be answered via a complete site survey. It is vital to know the area of land available for constructed wetland technology, since the efficiency of the completed system is a direct function of its size. Calculating the gradient of the site (and especially the difference in height between the influent and effluent points of a wetland) is critical if the project budget dictates that the treatment system should be gravity flow. Initial plans to install a Successive Alkalinity Producing System (SAPS)[11] at Quaking Houses were deemed

TABLE 4. Chemical quality of the Stanley Burn mine water discharge.

PARAMETER	
Flow-rate (L/min)- 14.8.95	17.1
Temperature (°C)	13.6
pH	4.5
Electrical Conductivity (µS/cm)	4400
Alkalinity (mg/L as $CaCO_3$)	0.0
$Acidity_{calc.}$* (mg/L as $CaCO_3$)	197.4
Iron (mg/L)	33.5
Aluminium (mg/L)	21.3
Manganese (mg/L)	9.7
Calcium (mg/L)	312
Magnesium (mg/L)	127
Sodium (mg/L)	429
Potassium (mg/L)	42
Sulphate (mg/L)	1790
Chloride (mg/L)	543

* $Acid_{calc} = 50(2Fe^{2+}/56 + 3Fe^{3+}/56 + 3Al/27 + 2Mn/55 + 1000(10^{-pH}))$ (7)

TABLE 5. Critical factors in site evaluation.

FACTOR	IMPLICATIONS
1. Land area	Feasibility of constructing large treatment systems.
2. Gradient	Potential for utilising gravity flow only.
3. Topography	Cut and fill requirements / disposal of excess material.
4. Substrate composition	Disposal of contaminated material / secondary pollution / construction of retaining structures.
5. Vehicular access	Transport of materials to site / plant access to site.
6. Bearing strength	Machinery access and manoeuvrability on site
7. Materials availability	Transport costs

unrealistic due to lack of sufficient head. Finally, a topographical survey will enable calculation of the quantities of material requiring excavation and, potentially, disposal.

The substrate on which the treatment system is to built must also be investigated. At Quaking Houses the site was historically used as the finings pond for the Morrison Busty Pit. As a result the material is heavily laden with both iron and aluminium. Upon excavation the buried material was exposed to oxidation and hydrolysis, and heavy rainfall subsequently washed these residues out of the material, forming substantial ochreous ponds where investigation pits had been dug. To prevent further occurrences of this nature at Quaking Houses excavation works are being kept to a minimum at this site.

Permeability tests of the substrate may also be necessary. Highly permeable substrate material would require the construction of effective retaining structures to prevent egress of mine water from the wetland.

Vehicular access is vital for transport of materials to the site. Even at a small site such as Quaking Houses in the order of 400 tonnes of clay, 100 tonnes of limestone, and 100 tonnes of compost will be required for construction of the wetland. A related consideration is the bearing strength of any ground on which heavy machinery will be working. Overall costs may escalate rapidly if the ground is difficult to work on, since plant hire for small works is often costed on a daily basis.

Finally, the availability and proximity of all materials required should be investigated. Transport costs may form a substantial percentage of the total project budget, particularly for small works such as Quaking Houses. As a result, at Quaking Houses, there has been a significant emphasis on accessing locally available materials, due both to the potential transport costs and not least because the project is community based.

It is at this point in the decision-making process that a remediation option and design is most appropriately selected. All of the findings of the site evaluation must be considered, as well as any legal and regulatory requirements. Figure 1 illustrates that these legal and regulatory requirements should be addressed as early as possible. This is because such issues, for example obtaining a licence to impound or divert water, may take time to resolve. If a project is running on a short timescale, as at Quaking Houses, significant delays may be incurred if a licence is required before construction work can proceed. Costs must be carefully calculated in order not to exceed total project funds. Major contributors to the total cost will include materials (and associated transport), construction, man power, and any chemical/biological analysis required. Given the uncertainty of, for example, machinery time on site depending on conditions, some form of contingency should be budgeted for (e.g. $\pm$ 5%). Remediation option and design may have to be reconsidered or adapted according to the outcome of the costing exercise.

When a remediation design has been prepared which meets regulatory requirements, which falls within the project budget, and that is commensurate with the results of the site evaluation, construction can begin. Subsequent monitoring results can be compared directly with the outcome of the original impact assessment (Figure 1) in order to give a quantitative measure of the success of the treatment scheme.

Conclusions

Current methods of impact assessment for mine water discharges[2][3] adequately quantify the detrimental effects of this now widespread aquatic pollution problem. However, it appears that the chemical nature of the discharge alone is not indicative, in its own right, of the impact a mine water discharge will have on a receiving watercourse. A thorough impact assessment must therefore consider the characteristic's of the receiving watercourse as well as of the mine water discharge itself.

An important element missing from current impact assessment methodologies is the inclusion of critical contaminant load in the assessment. For mine water discharges the critical contaminant load is usually either the iron load or the acidity load. Inclusion of one or both of these variables in an impact assessment would enable quantification of the potential impacts of a mine water on the water resources/supply of a catchment, an issue which is not addressed in current impact assessment methodologies. Further, the iron/acidity load is the critical variable in the design of constructed wetlands for mine water remediation. Since load should be measured over a full year (due to seasonal variation) valuable time and resources could be saved if it was measured from the outset of any investigation.

Experiences at Quaking Houses, County Durham, where an engineered wetland is currently under construction, have highlighted the need for an efficient approach to mine water impact assessment and remediation initiatives. Beyond the initial impact assessment the need for a thorough and organised approach to site evaluation and selection of treatment options is vital. After preliminary 'scoping' of treatment options a thorough site evaluation should proceed. This should include factors such as land area, site gradient and topography, as well as issues of vehicular access and materials availability. This will enable correct selection of the appropriate remediation technology. Following a calculation of the total cost of the resultant design it may be modified or amended if it exceeds the total budget available. Post-construction monitoring results could be compared directly with the already completed impact assessment, as a guide to the efficiency and effectiveness of the system installed.

Due to the very limited financial resources available for mine water impact assessment and remediation schemes in the UK, approaching such projects both effectively and efficiently is critical to their success. Evidence from the construction of a wetland at Quaking Houses strongly suggests that the methodology for assessment and remediation outlined above is just such an approach, and may serve as a useful foundation upon which future researchers may build.

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